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Analysis of rainfall trends of two complex mountain river basins on the southern slopes of the Central Himalayas

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ABSTRACT

Understanding rainfall characteristics plays a vital role in sustainable watershed development and management, but at the same time it is challenging in mountainous regions, due to its topography complexities. This study investigates the seasonal along its associated months and annual rainfall characteristics and their variations over two distinct river basins; Kaligandaki in central west and Koshi in eastern Nepal, located on the southern slopes of the central Himalayas, which is crucial to the research of the climate change in these regions. The rainfall data series over the period of 34-year (1981–2015) of 43 stations between the elevation range of 143 m asl to 3870 m asl was used for this study. The analysis was carried out to assess the significance of rainfall trend along with its magnitude followed by its abrupt shift by using the Mann-Kendall test, Sen's test and Sequential Mann-Kendall test respectively. Furthermore, multitaper method was used to confirm the influence of large-scale circulation indices over the study area. An increasing pattern of rainfall from south to north was observed throughout all season in Koshi basin which was not seen in the Kaligandaki basin, indicating the effects of orography along with monsoon. Both basins share a similar pattern of rainfall between annual and monsoonal rainfall, supporting that both basins are dominated by the monsoon. The transition months between the seasons showed almost similar spatial distribution but different from other months of respective seasons. The results showed that the seasonal and annual rainfall declined in most of the stations of both the basins, except during pre-monsoon where it showed increased rainfall. But only a few stations showing such changes were statistically significant. In fact, these noticeable significant decreases were observed especially in the southern and northern region of Koshi basin while in Kaligandaki basin, it was found either in central or in the southern region. Furthermore, the trend shift analysis identified change points during 1980s or early 1990s, but most significant shifts were observed in recent years with some exceptions. Spectral analysis showed significant peaks at periodicity ranging 2–5 years, suggesting a potential association with Quasi-Biennial Oscillations (QBO) and El Niño-Southern Oscillation (ENSO).

1. Introduction

Rainfall is one of the most important meteorological forcing terms of the hydrological system. Understanding the changes in rainfall can be taken as the need of time as it affects the terrestrial hydrological system and water resources vigorously. Hence, detail information about spatial and temporal variations in rainfall characteristics is essential to predict the near future possible changes in the hydrological system along with water resources responses to these variations. Looking at a global scale, the hydrological cycle is expected to be intensified with the increased surface temperature which by increasing the moisture-holding capacity of the atmosphere results in heavy rainfall over a short time scales and also affects the temporal distribution of the rainfall (Berg and Haerter, 2013; Haerter et al., 2010; Haerter and Berg, 2009; Lenderink and van Meijgaard, 2008; Westra et al., 2013a, 2013b). For instance, a study carried out by Alexander et al. (2006) found an increasing trend in more extreme precipitation events on a global scale, which is also continuing over the recent decades (Asadieh and Krakauer, 2015; Donat et al., 2013; Donat et al., 2016; Lehmann et al., 2015; Min et al., 2011; Vimal et al., 2015; Westra et al., 2013a). These

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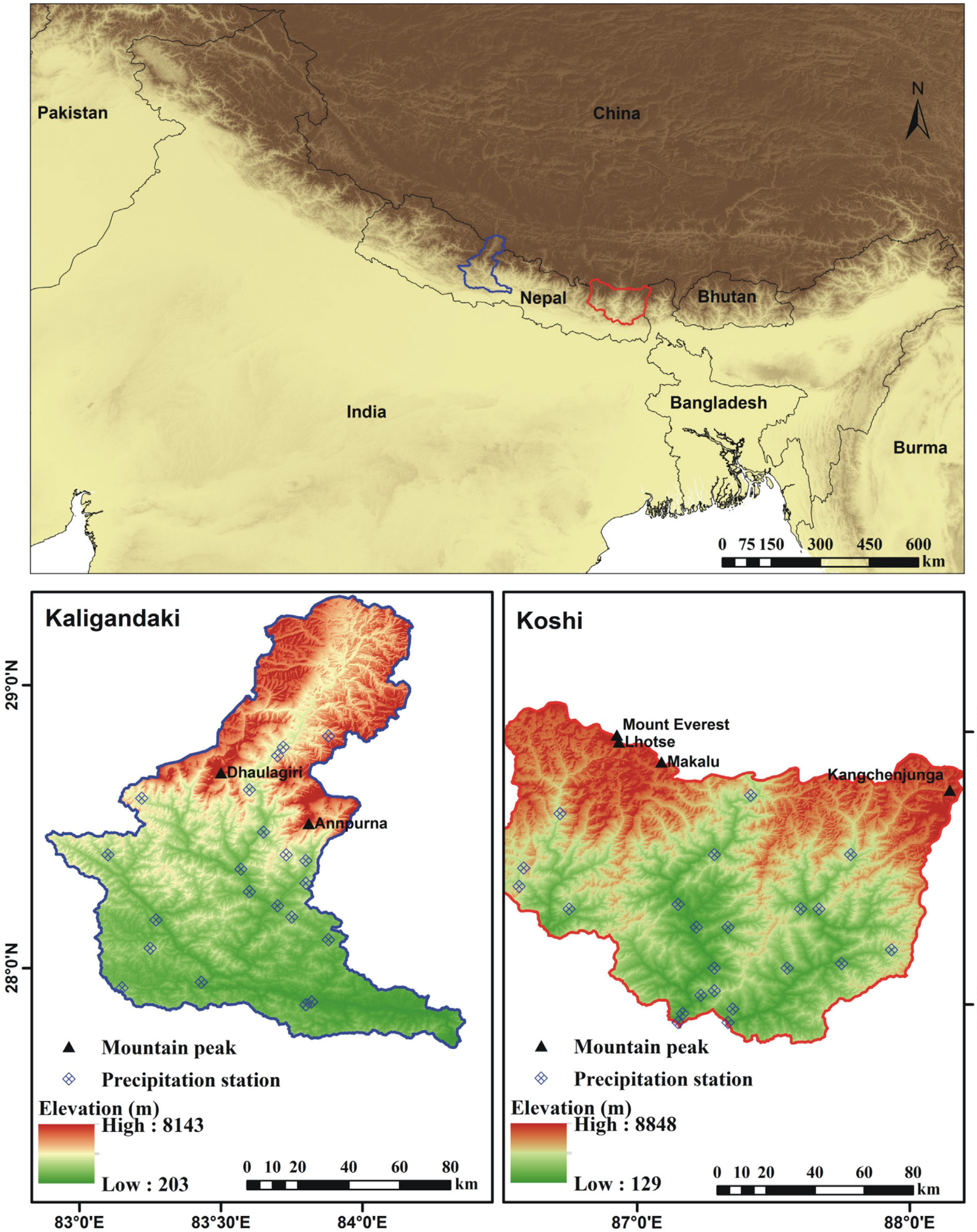


Fig. 1. Topographical map of study area showing spatial distribution of meteorological station.

extreme rainfall events eventually affect the mean annual rainfall or rainfall seasonality (Kumar, 2013). Also, Dore (2005) revealed a continued increase in annual land precipitation in the middle and high latitudes of the Northern Hemisphere likely by 0.5% to 1% per decade apart from Eastern Asia. Likewise, Wang et al. (2008) showed an increasing trend of rainfall in East Asia numerically with atmospheric general circulation models and also pointed out that raised in warming driving to increased rainfall. Meanwhile, a study carried out by Turner and Annamalai (2012) resulted in a decrease in rainfall in South Asia since 1950s. However, Liu et al. (2011) used tree- ring based reconstructions of seasonal to annual precipitation data and showed an increase in precipitation in central northern Himalayas for the period of 1980s to 2008. Joshi and Pandey (2011) resulted no any trend in annual rainfall over whole India and specific Indian regions for a study period of 100 years while Kumar et al. (2010) analyzed 135 years of monthly rainfall data over 30 sub-divisions of India and reported large spatial and temporal variations in rainfall trend such that the mean annual and monsoon rainfall is decreasing at national wide. Roxy et al.

(2015) investigated rainfall trends and its dynamics along the Ganges-Brahmaputra basins and the Himalayan foothills and suggested that summer monsoon rainfall was decreasing since 1901–2012 over parts of South Asia, moreover, significant decrease in rainfall was observed over the central-east and northern regions of India. Even some studies compared northern and southern sides of the Everest region and indicated in decreasing trend towards the southern slope since early 1990s (Xu et al., 2008; Yang et al., 2006).

As an increasing number of scientific studies indicates that the mountainous regions are undergoing change due to recent warming (IPCC, 2007, 2013), Nepal being mountainous country, directly or indirectly it affects the rainfall pattern of these regions. Even Yao et al. (2012) pointed out in their research indicating strong evidence about decreasing precipitation along the Himalayas during 1979 to 2010 with a real decreasing trend commencing from early 1990s. Rainfall is taken as only relevant water input to these regions. So, the temporal and spatial variability of rainfall has been identified as important for mountainous regions (Kansakar et al., 2004). Previous studies showed a strong relationship between rainfall and elevation (Higuchi et al., 1982; Ichiyanagi et al., 2007; Rocky et al., 2018; Shrestha et al., 2012a; Yang et al., 2018) in Nepal which may be due to a decrease in water holding capacity of the lifted air. The lifted air gets further more rises causing a decline in water content because of higher rainfall while at some elevation, rainfall decreases as a result of diminished water content. However, Salerno et al. (2015) resulted in a decrease in rainfall with similar values in higher and lower elevations in southern slopes of Mt. Everest. To be precise about rainfall trend in Nepal, most of the previous studies didn't identify any distinct results about rainfall trend (Baidya et al., 2008; Malla, 2009; Shrestha et al., 2000). Neither other parts of the country showed distinct rainfall variation (Devkota, 2014; Khatiwada et al., 2016; Panthi et al., 2015; Thapa and Kayastha, 2015).

Lately, in the context of Nepal, water is taken as a scarce resource as its availability is decreasing day by day since water is taken as a vital resource not only for drinking purpose but also for irrigation, electricity generation and much more. So, for proper water resource planning and management, rainfall trend analysis is a must. It has been reported that local or regional scale planning is far better than the global scale observations (Barsugli et al., 2009; Raucher, 2010). Hence, there is a significant gap of knowledge on local scale study for assessing the historical trends. Although Koshi and Kaligandaki basins of Nepal which lie on the eastern (Province 1) and central-western (Province 4) part of the country respectively, very few studies was carried out regarding rainfall trend analysis (Nepal, 2012; Panthi et al., 2015; Sharma et al., 2000). However, these studies do not provide any clear view of rainfall variation. This means that there still exists lack of proper understanding about past and present rainfall condition for different time series within the sub-basins of Koshi and Kaligandaki river basins. Moreover, these aforementioned studies either do not cover recent years or do not cover spatial variability of different rainfall time series, indicating that one cannot be certain about recent rainfall changes.

In this study, an attempt has therefore been made to form a better view of the spatio-temporal fluctuation in the seasonal along with its transition months and annual rainfall series in the sub-basins of Koshi river basin (province 1) and Kaligandaki basin (province 4), eastern and central-western region respectively of Nepal. The findings will likely be beneficial to the research of the climate change in these regions and the sustainable development of the local water resources of the study area for better preparedness for future.

2. Climatology of the study region

Koshi basin (trans-boundary) is situated between the latitudes of 26°51′2.34″N and 29°8′15.45″N and longitude of 85°39′32.58″E and 88°57′17.26″E with an area of about 41,612 km^2 whereas Kaligandaki basin (trans-Himalayan) lies between the latitudes of 27°42′59.16″N and 29°17′30.35″N and longitude of 82°52′59.76″E and 84°21′57.59″E with an area of about 11,473 km^2 (Fig. 1). The elevation of Koshi basin ranges between 120 and 8848 m asl whereas, for Kaligandaki basin, it ranges between 203 and 8143 m asl, indicating variation in topography from plain to high Himalayas (Shrestha and Aryal, 2011). Both the basins consist of tropical climate in the southern part to the cold arid steppe in the northern part (Karki et al., 2016). Both basins are dominated by the southeast monsoon causing heavy rainfall during summer (Kattel et al., 2015; Shrestha et al., 2000) but the amount may differ with stations as topography play a vital role in regulating monsoonal air flow in mountain system (Barros et al., 2000; Barros and Lang, 2003; Kansakar et al., 2004). Normally, rainfall amounts decrease at higher elevations (Ichiyanagi et al., 2007; Shrestha et al., 2012a; Yao et al., 2012), but recently, Yang et al. (2018) showed that monsoonal rainfall amount remains uniform between 3600 and 5000 m asl of Koshi basin. The westerlies originated in the Mediterranean region (Dimri and Mohanty, 2009; Syed et al., 2010), causes winter rainfall especially over a northwestern mountainous region of the country and played a vital role for the formation of snow/glaciers in this region (Dimri et al., 2015).

3. Data and methods

Forty-three meteorological stations with comparatively long data records, i.e., twenty-two on the Koshi basin and twenty-one on the Kaligandaki basin, were used for data collection. The elevation of all the stations range between 143 and 3870 m above sea level (asl; Table 1 and Fig. 1). Due to the unavailability of the long-term dataset, daily observed rainfall data from January 1981 to December 2015 was used in this study. All dataset were collected from the Department of Hydrology and Meteorology (DHM), Government of Nepal.

Initially, only stations with < 10% of missing values of climatic data set were selected for the quality check and analysis. Homogeneity tests were assessed using four different methods; i.e., Pettitt's (Pettitt, 1979), standard normal homogeneity (SNHT) (Alexandersson, 1986), Buishand's (Buishand, 1982) and Von Neumann's test (Von Neumann, 1941). Detail methodological procedures are available in their respective earlier research. Based on the above test, only homogeneous datasets are used in this study. Additionally, monthly total rainfall data was derived from daily rainfall values whereas, total annual rainfall data was obtained by adding total monthly rainfall data after filling missing values from the daily rainfall data series. The normal ratio method was used to fill the missing values for a particular station (Singh, 1992). Furthermore, the twelve months are divided into winter (DJF: December, January and February), pre-monsoon (MAM: March, April and May), monsoon (JJAS: June, July, August and September) and post-monsoon (October and November) for the seasonal analysis.

The MK test (Kendall, 1970; Mann, 1945) was applied to evaluate the monotonic trend of the time series of monthly, seasonal and annual rainfall values. This test is taken as better than the parametric tests since it is more resilient to outliers (Lanzante, 1996). In MK trend test, the null hypothesis assumes that there is no trend and also the data are random and independent against the alternative hypothesis which assumes that there is a trend in time series. Furthermore, Sen's estimator of the slope (Sen, 1968) was used to analyze the trend magnitude as it was calculated as the median of all possible slopes. This method evaluates robust estimation of a trend which needs equally spaced data time series. To perform these trend tests, MAKESENS program (Microsoft Excel template) was used which is provided by Finnish Meteorological Institute (Salmi, 2002) and statistical significance above a 95% confidence interval was considered. Many previous studies used this program for detecting and estimating trends in time series (Fan et al., 2012; Fan and Wang, 2011; Nepal, 2016; Santos and Fragoso, 2013). Missing values are taken into account and no any particular distributions are required for the needed data, which are some of the pros of this template. Also, outliers do not affect Sen's method in this template. Finally, Kriging interpolation method was used for mapping the spatial pattern

Table 1
Basic information of the stations of both basins.

Basin	Index No.	Name	Latitude (N)	Longitude (E)	Elevation (masl)
Koshi	1309	Tribeni	26°56′	87°09′	143
	1322	Machuwaghat	26°58′	87°10′	158
	1321	Tumlingtar	27°17′	87°13′	303
	1308	Mulghat	26°56′	87°20′	365
	1305	Leguwaghat	27°08′	87°17′	410
	1420	Dovan	27°21′	87°36′	763
	1325	Dingla	27°22′	87°09′	1190
	1419	Phidim	27°09′	87°45′	1205
	1307	Dhankuta	26°59′	87°21′	1210
	1306	Munga	27°02′	87°14′	1317
	1303	Chainpur	27°17′	87°20′	1329
	1301	Num	27°33′	87°17′	1497
	1314	Terhathum	27°08′	87°33′	1633
	1304	Pakhribas	27°03′	87°17′	1680
	1405	Taplejung	27°21′	87°40′	1732
	1403	Lungthung	27°33′	87°47′	1780
	1406	Memeng Jagat	27°12′	87°56′	1830
	1203	Pakarnas	27°26′	86°34′	1982
	1204	Aisealukhark	27°21′	86°45′	2143
	1219	Salleri	27°30′	86°35′	2378
	1317	Chepuwa	27°46′	87°25′	2590
	1202	Chaurikhark	27°42′	86°43′	2619
Kaligandaki	701	Ridi bazar	27°57′	83°26′	442
	810	Chapkot	27°53′	83°49′	460
	726	Garakot	27°52′	83°48′	500
	609	Benibazar	28°21′	83°34′	835
	805	Syangja	28°06′	83°53′	868
	614	Kushma	28°13′	83°42′	891
	605	Baglung	28°16′	83°36′	984
	606	Tatopani	28°29′	83°39′	1243
	722	Musikot	28°10′	83°16′	1280
	725	Tamghas	28°04′	83°15′	1530
	613	Karki Neta	28°11′	83°45′	1720
	814	Lumle	28°18′	83°48′	1740
	715	Kahanchikot	27°56′	83°09′	1760
	821	Ghandruk	28°23′	83°48′	1960
	615	Bobang	28°24′	83°06′	2273
	607	Lete	28°38′	83°36′	2384
	616	Gurja Khani	28°36′	83°13′	2530
	604	Thakmarpha	28°45′	83°42′	2566
	619	Ghorepani	28°24′	83°44′	2742
	601	Jomsom	28°47′	83°43′	2744
	608	Ranipauwa	28°49′	83°53′	3609

of trends from point data.

The sequential version of the Mann-Kendall (SQMK) test (Sneyers, 1990) was then performed to test assumption about begin of a trend in the rainfall time series. To detect the abrupt shift point in hydro-climatic variables, the sequential Mann-Kendall test has been used by several researchers (Bari et al., 2016; Hosseinzadeh Talaee et al., 2014; Jones et al., 2015; Sharma et al., 2016; Zhang et al., 2012). For this study, 0.05 significant level was used for both MK test and SQMK test. The sequential Mann-Kendall test allows identification of the approximate time of occurrence of a trend from the intersection point of the forward and backward curves of the test statistic. If the interaction point is significant at 0.05, then the critical point of change is at that point. If the curve lies within the confidence limits before the shift point, the identified change is abrupt. Also, the exceeded parts of the curve indicate the time domain of the abrupt change. Hence the sequential Mann-Kendall test is an efficient way by which the starting time of a trend is located.

An attempt was also made to interpret and explain the periodicity on annual, monsoon and winter rainfall. For this purpose, Multi-Taper Method (MTM) (The SSA-MTM Toolkit) (Vautard et al., 1992) was used as it is a non-parametric spectral method. It is used to access a better estimate of the distribution of the variance of the series versus the frequency. In this method, tapers are used to minimize the variance of spectral estimates to prevent spectral leakage. The red noise background is calculated by reducing the different odd characters between an analytical autoregressive red noise spectrum and the weighted multitaper spectrum. The statistical significance of the multitaper spectrum is tested using the chi-squired test against a red noise. A brief description of the methodologies involved in this study can be found in the aforementioned literature in this chapter.

4. Results and discussion

4.1. Spatial variability of rainfall

4.1.1. Seasonal spatial variation

Rainfall is only pertinent water input to the mountain regions. Spatial variability of rainfall has been identified as important for mountainous regions such as study area, where the mountainous relief plays significant role in yielding local rainfall pattern (Kansakar et al., 2004). Hence, Figs. 2 and 3 gives more detail information about spatial distribution of the mean seasonal rainfall regime at three sub-basins (Tamor, Arun and Dudhkoshi, from east to west) of Koshi basin and Kaligandaki basin. In case of Koshi basin, the southern parts of all sub-basins have relatively low rainfall during all seasons. Most parts of southern region lying in valley between the southern frontal mountains and northern elevated mountains making it a drier zone as explained by Bohner (2006) also coincide with their results. Increase in rainfall from

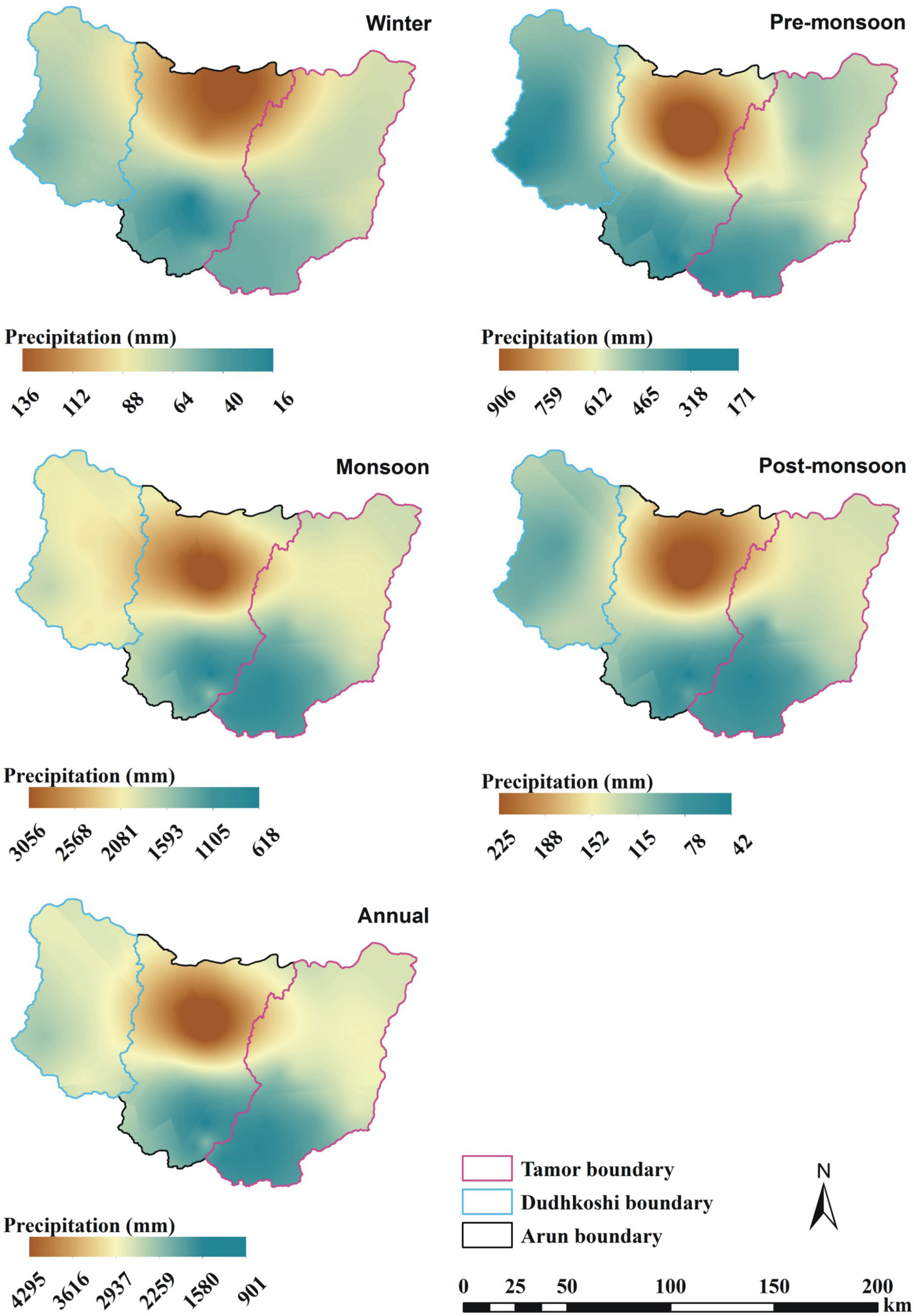


Fig. 2. Spatial distribution of the seasonal and annual rainfall for Koshi basin by Kriging method during 1981–2015.

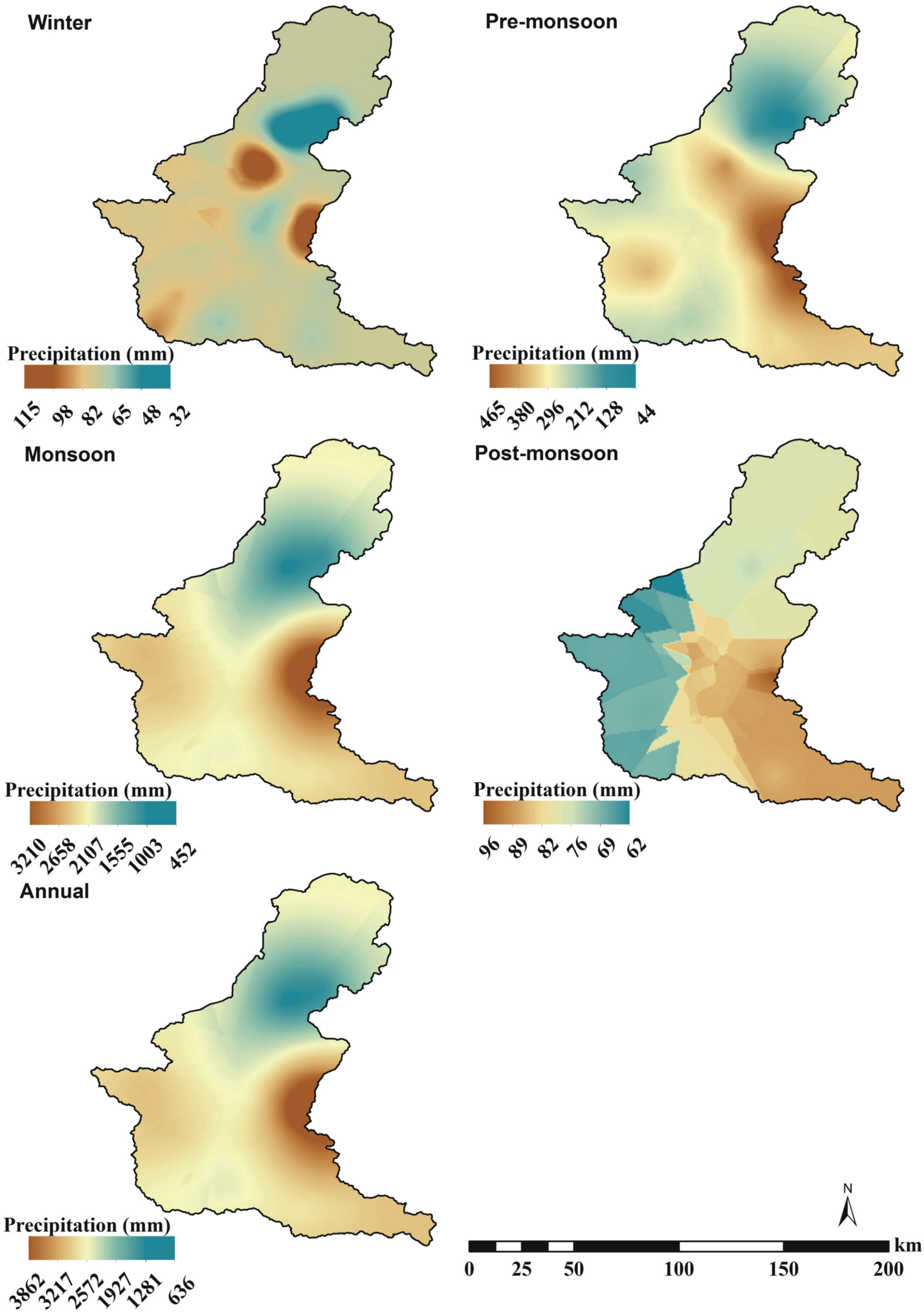


Fig. 3. Spatial distribution of the seasonal and annual rainfall for Kaligandaki basin by Kriging method during 1981–2015.

south-west to north-east direction was found throughout all seasons in Tamor and Dudhkoshi sub-basins. While, in Arun sub-basin, similar pattern of increase in rainfall from south to north was found throughout all seasons along with high rainfall pocket area in the upper northern region. The reason behind rainfall pocket area is due to large orographic differences as it lies in the influence of windward side of Makalu range (Fig. 1) (Houze, 2012; Kansakar et al., 2004; Romatschke and Houze Jr, 2011; Shrestha et al., 2012b). During monsoon season, rainfall ranges between 618 mm and 3056 mm showing low rainfall in southern part while highest at central part which further supports the argument. Even though, almost similar patterns of rainfall were found during pre-monsoon and post-monsoon seasons with monsoon season, but they range differently. Such as rainfall during pre-monsoon ranges between 171 mm and 906 mm while during post-monsoon, it ranges between 42 mm and 225 mm. During winter season, except the rainfall pocket part of Arun sub-basin, all other parts follow the same rainfall pattern as other seasons. Rainfall pocket area spreads little bit more in northern region indicating some influence of westerly synoptic system (Dimri et al., 2015; Kattel et al., 2013). Furthermore, it is more interesting going through the spatial variation in monthly transition period between seasons (Fig. S1). For instance, spatial variation in the months of May and June which is a transition period between pre-monsoon and monsoon season, show almost similar pattern but different from other months of respective season which is actually associated with warm subtropical high and cold westerly troughs (Yasunari, 1976). Similarly, other transition periods i.e., September–October, November–December and February–March also support the above statement of spatial pattern between the post-monsoon, winter and pre-monsoon respectively. There are perhaps different regions involved for such spatial pattern during the transition months. For instance, rainfall decreases in the month of October which is actually after monsoon, even though there is presence of moisture in the air indicating the effect of westerly disturbance associated with sub-tropical jet. Likewise, post-monsoon ends with the effects of westerly troughs accompanied by cold outbreaks integrated in the sub-tropical jet. However, during the transition period between winter and pre-monsoon, the effect of westerly trough integrated with sub-tropical jet is minimum or null causing change in rainfall. Even though large-scale weather system affects Nepal's precipitation (Gaire et al., 2017; Madan and Ikeda, 2009; Shrestha et al., 2000), note that the local topography of mountainous basins dominants on spatial variation of rainfall (Kansakar et al., 2004). Despite of different spatial variation range between months, the most common result was found in the upper northern part of Arun basin as a high rainfall pocket region and southern part (especially Arun and Tamor) showed low rainfall which further supports the above argument and also coincides with previous studies (Action, 2009; Dhar and Nandargi, 2005; Ichiyanagi et al., 2007; Kansakar et al., 2004; Karki et al., 2017; Shrestha, 2000).

In the case of Kaligandaki basin, monsoon rainfall dominates annual rainfall ranging between 452 mm and 3210 mm. The northern region of the basin is drier whereas lower eastern region is wettest indicating effect of topography since northern region lies on the leeward side and lower eastern region lies on the windward side (Houze, 2012; Romatschke and Houze Jr, 2011). Almost similar pattern of rainfall distribution was also found during pre-monsoon season, however, rainfall amount was different ranging between 44 mm and 465 mm. Rainfall amount during post-monsoon and winter season ranges from 62 to 96 mm and 32–115 mm respectively, but rainfall was not well distributed spatially within the basin. Like in Koshi basin, the spatial variation in monthly transition periods between seasons displayed uniquely (Fig. S2) along with exception. Such as, spatial variation in the months of May and June, which is transition period between pre-monsoon and monsoon season, show almost similar pattern, but different from other months of the respective season. Similarly, other transition periods i.e., September–October, November–December and February–March also support the above statement between the post-monsoon, winter and pre-monsoon respectively. Exception being the spatial variation in the months of June and September, which shows almost similar pattern indicating the effect of monsoon as well as topography. Despite of different spatial variation ranges between months, the most common result was found in the upper central part as low rainfall region and lower eastern part showed high rainfall pocket zone indicating the influence of topography and surrounding microclimate and also coincides with previous studies (Action, 2009; Dhar and Nandargi, 2005; Ichiyanagi et al., 2007; Kansakar et al., 2004; Karki et al., 2017; Shrestha, 2000).

4.1.2. Annual spatial variation

Nepal's rainfall is dominated by monsoon rainfall. Hence, spatial variation of annual rainfall is found similar to the monsoon rainfall for both the basins (Figs. 2 and 3). The highest rainfall occurs at the upper central part of Koshi basin (Arun sub-basin), while the lowest amount of rainfall is observed at the lower southeastern part of this basin (Tamor sub-basin) where the rainfall values range between 901 and 4295 mm. Similarly, the highest rainfall is observed at central eastern part of Kaligandaki basin, while upper northern part of this basin observes the lowest rainfall such that the rainfall values range between 636 and 3862 mm. The result somehow indicates that rainfall increases towards northward at high altitude with some exceptions. But this variability is caused due to the close linkage between water vapor source with monsoon intensity along with the effect of topography (Barros et al., 2000; Bookhagen and Burbank, 2010; Ichiyanagi et al., 2007; Kansakar et al., 2004; Yao et al., 1995). As mentioned before, there are also noticeable pockets of highest rainfall around northern part of the Arun sub-basin and lower eastern part of Kaligandaki basin, since they lie on the windward side and it coincides with the results of previous studies (Dhar and Nandargi, 2005; Kansakar et al., 2004; Karki et al., 2017; Shrestha et al., 2000). However, the lower southern part of Tamor and Arun sub-basins and upper northern part of Kaligandaki basin get relatively low rainfall as mentioned earlier. Moreover, annual rainfall of Koshi basin is not spatially variable (except central part of Arun sub-basin) compared to the Kaligandaki basin since it lies adjacent to the Bay of Bengal and controls the climate by monsoon throughout the summer months. In case of Kaligandaki basin, apart of monsoon duration and effects of topoclimate, westerly synoptic system (especially in winter) plays significant role on spatial variation of rainfall (Dimri et al., 2015; Karki et al., 2018).

4.2. Trend analysis

4.2.1. Seasonal rainfall trend

Spatial variation of rainfall is not enough to be familiar with the rainfall condition, past information is also must. For this purpose, long-term analysis of rainfall was also carried out for both of the study areas. The results of the seasonal Mann-Kendall test (Table 2 and Figs. 4 and 5) showed decreasing trend in most of the stations except pre-monsoon rainfall time series of both the basins. During pre-monsoon season, most of the stations (14 stations of Koshi basin and 16 stations of Kaligandaki basin) showed increasing trend. But to be precise, none of the stations of Koshi basin showed significant trend while only one station (Ghorepani) of Kaligandaki basin showed a significant increasing trend. Similarly, during monsoon season, two stations (Ridibazar and Bobang) of Kaligandaki basin and three stations (Dhankuta, Phidim and Munga) of Koshi basin also showed a significant decreasing trend. Thakmarpha station of Kaligandaki basin showed significant decreasing trend during post-monsoon season while Num station of Koshi basin showed a significant increasing trend. During winter season, only one station (Jomsom) of Kaligandaki showed a significant increasing trend, while four stations (Munga, Chepuwa, Chaurikhark and Aisealukhark) of Koshi basin showed a significant decreasing trend. This result somehow shows similarity with the study carried out by Duncan et al. (2013) where their result showed an increase in pre-monsoon rainfall trend

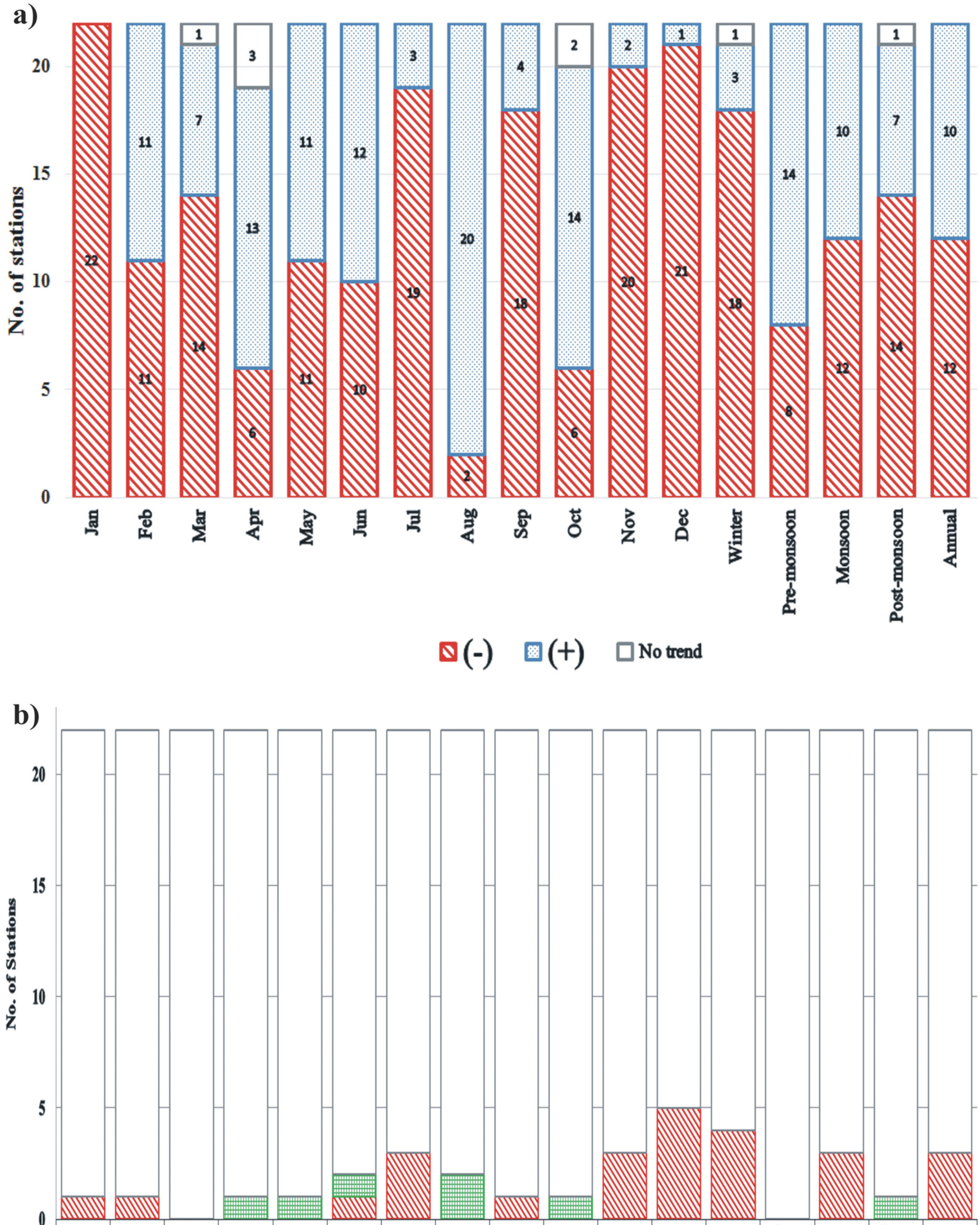
Table 2
Results of Mann Kendall test statistic (Z) for seasonal and annual rainfall during 1981–2015. *, ** and *** bold values show statistical significant increase and decrease at 1%, 5% and 10% confidence level. Negative and positive values indicate the decreasing and increasing trends.

Basin	Station Name	Annual	Winter	Pre-monsoon	Monsoon	Post-monsoon
Koshi	Dhankuta	−1.90	−1.72	1.36	**−2.44***	−0.4
	Mulghat	0.31	−1.15	0.91	0.03	0.01
	Terhathum	0.03	−0.11	0.99	−0.26	−0.34
	Lungthung	1.19	−0.64	0.54	1.14	0.68
	Taplejung	−0.23	−1.31	−0.68	0.03	−0.06
	Memeng Jagat	−1.85	−1.59	−1.68	−1.33	−1.05
	Phidim	**−2.36***	−1.04	−1.08	**−2.22***	1.02
	Dovan	0.34	0.33	0.48	−0.14	0.00
	Num	0.77	0.00	1.70	0.77	**2.56***
	Chainpur	−0.80	−1.32	0.71	−0.62	0.34
	Pakhribas	−0.31	−0.53	1.45	−0.91	−0.19
	Leguwaghat	0.11	0.24	0.11	0.68	−0.06
	Munga	**−2.33***	**−2.16***	−0.11	**−2.78****	−0.41
	Tribeni	−0.60	−1.16	0.67	−0.34	−0.17
	Chepuwa	−1.05	**−2.02***	−0.80	−0.43	−0.40
	Tumlingtar	0.94	−0.90	0.80	0.71	0.89
	Machuwaghat	0.68	0.09	0.23	0.68	0.11
	Dingla	−0.23	−1.36	−0.65	0.03	−0.11
	Chaurikhark	0.26	**−3.95*****	0.67	0.60	−0.88
	Pakarnas	−0.71	−1.60	−0.80	−0.62	−0.54
	Aisealukhark	**−2.34***	**−2.61****	−1.65	−1.55	−1.09
	Salleri	0.77	−0.40	0.99	0.40	−0.74
Kaligandaki	Ridi bazar	**−2.93****	−0.54	−0.54	**−2.67****	−1.37
	Chapkot	−1.53	−0.23	−0.51	−1.39	−0.45
	Garakot	−0.71	0.75	−0.34	−0.37	−0.53
	Benibazar	−0.31	0.98	−0.14	−0.65	−0.34
	Syangja	0.51	−1.21	0.03	0.40	0.85
	Kushma	−0.37	−0.17	0.48	−0.54	0.31
	Baglung	−0.16	0.04	−0.43	−0.57	0.60
	Tatopani	0.65	−0.10	0.94	0.99	−0.82
	Musikot	**2.56****	0.96	0.69	1.75	−1.04
	Tamghas	−0.68	0.17	0.99	−0.80	−0.61
	Karki Neta	0.00	−0.45	1.05	−0.40	0.77
	Lumle	0.23	−0.14	0.18	0.51	0.14
	Kahanchikot	−1.82	−0.62	0.20	−1.42	−1.38
	Ghandruk	1.39	−1.56	1.25	1.39	0.94
	Bobang	**−2.39***	−1.43	0.14	**−2.44***	−0.45
	Lete	1.82	0.81	1.42	0.94	0.48
	Gurja Khani	1.08	−1.22	0.16	1.24	0.16
	Thakmarpha	0.43	1.55	0.89	−0.18	**−2.07***
	Ghorepani	−0.82	−1.42	**2.81****	−1.11	−0.53
	Jomsom	1.42	**2.34***	0.14	1.56	−0.24
	Ranipauwa	0.85	0.51	0.21	0.09	0.61

while decrease during monsoon and winter season. The result is also consistent with some other studies carried out over Koshi and Kaligandaki basins along with some exceptions which conceivably due to different datasets time period and methods involved (Dahal et al., 2016; Karki et al., 2017; Panthi et al., 2015). The aforementioned results also showed that the rainfall trend is inhomogeneous for different stations indicating variability in rainfall amount which is due to various thermodynamical and orographic processes. This is also related to the weakening in monsoon due to a decrease in land-sea thermal gradient (Roxy et al., 2015) along with strengthening of westerlies (Zhao et al., 2012). Furthermore, a decrease in rainfall is feasibly associated with the aerosol emissions too (Bollasina et al., 2011).

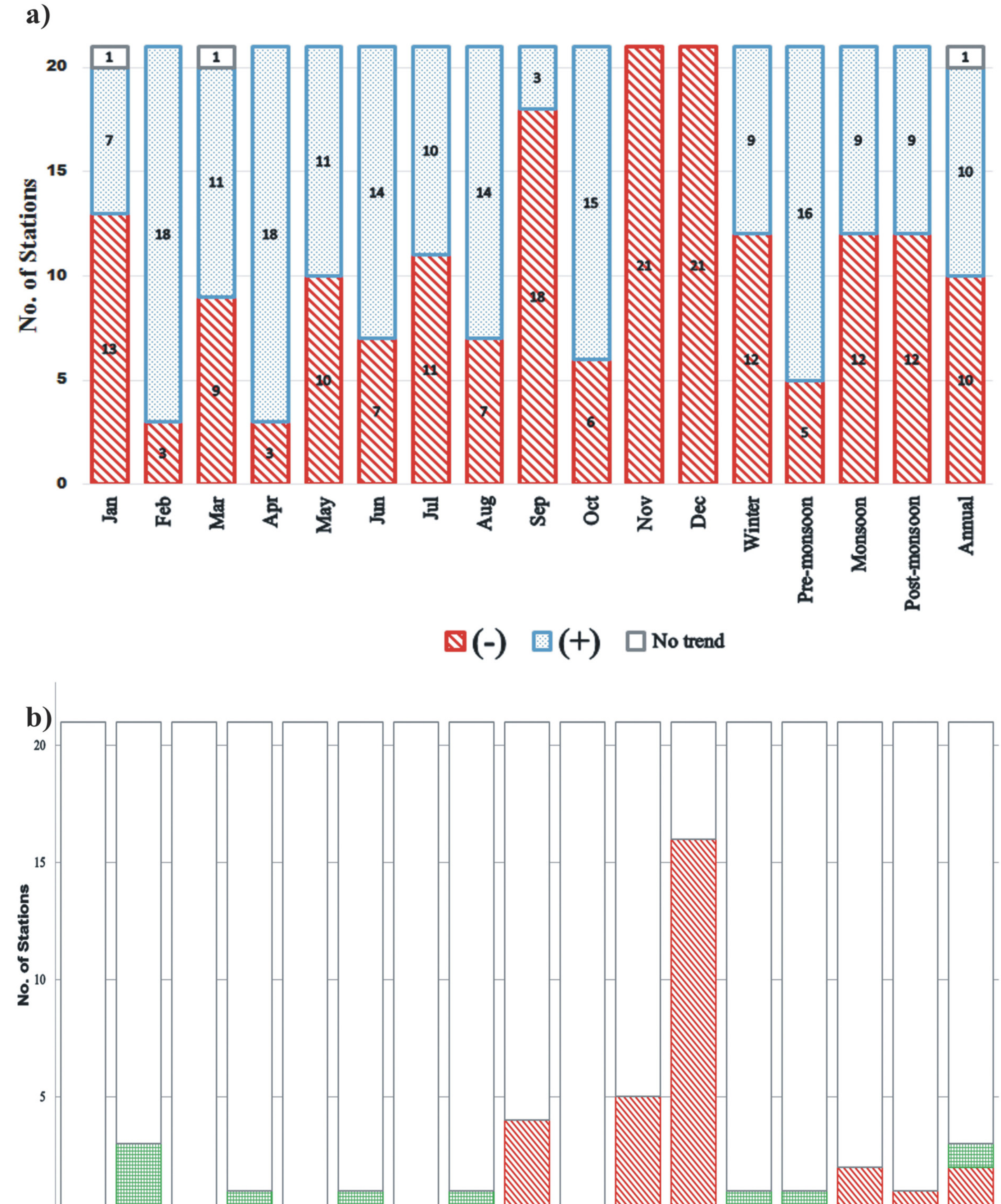
Fig. 6 shows the results of spatial distribution of seasonal rainfall trend analysis of three sub-basins of Koshi basin. During pre-monsoon season, southern part of Dudhkoshi basin exhibited negative slope whereas northern part showed positive slope. Likewise, for Tamor basin, eastern part exhibited mild negative slope whereas western part showed positive slope. Central part of the Arun sub-basin was indicated by positive slope while its peripheral region showed negative slope. As a whole, the trend slope varied between −4.0 mm/year and 6.8 mm/year. Similarly, during monsoon season, the stations showing significant decreasing trend lies in lower southern part of Tamor and Arun sub-basins and showing mild negative slope at southern part whereas positive slope at northern part of throughout the basin. The trend slope varied between −5.9 mm/year and 2.9 mm/year. Meanwhile, spatial distribution of positive trend slope for post-monsoon season showed almost similar pattern that of pre-monsoon, however, almost every part of all sub-basins (except central part of Arun sub-basin) showed mild negative slope even though it varies between −1.3 mm/year and 5.7 mm/year. Also, different spatial trend slope was exhibited during winter season than that of monsoon season, such that mild negative slope at northern part of all sub-basins whereas mild positive slope at southern part. The trend slope varied between −2.6 mm/year and 0.3 mm/year. Likewise from Fig. 7, spatial distribution of trend slope for Kaligandaki basin for pre-monsoon season showed mild positive slope throughout the basin ranging from 0.4 to 1.7 mm/year. During monsoon season, stations with significant decreasing trend lie on the lower south-west part of the basin indicating negative slope. Central to northern part of the basin showed mild positive slope. The basin's trend slope varied between −4.6 mm/year and 3.7 mm/year. Meanwhile, during post-monsoon season, except lower eastern part, all other parts showed mild negative slope even though its slope varies between −0.8 mm/year and 0.4 mm/year. During winter season, almost the lower part of the basin exhibited negative slope while upper part showed positive slope. The trend slope varied between −1.7 mm/year and 0.8 mm/year.

For Koshi basin, most of the months showed decreasing trend with some exceptions showing no trends at all (Table 3 and Fig. 4). However,



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Winter	Pre-monsoon	Monsoon	Post-monsoon	Annual
No sig	21	21	22	21	21	20	19	20	21	21	19	17	18	22	19	21	19
(+)	0	0	0	1	1	1	0	2	0	1	0	0	0	0	0	1	0
(-)	1	1	0	0	0	1	3	0	1	0	3	5	4	0	3	0	3

Fig. 4. a) No. of stations of overall negative and positive trends for Koshi basin; b) Rainfall trends considering monthly, seasonal and annual scale data series over the periods 1981–2015 in Koshi basin. No of stations (out of 22) in MK test find significant positive-negative trends in 95% confidence levels.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Winter	Pre-monsoon	Monsoon	Post-monsoon	Annual
No sig	21	18	21	20	21	20	21	20	17	21	16	5	20	20	19	20	18
(+)	0	3	0	1	0	1	0	1	0	0	0	0	1	1	0	0	1
(-)	0	0	0	0	0	0	0	0	4	0	5	16	0	0	2	1	2

Fig. 5. a) No. of stations of overall negative and positive trends for Kaligandaki basin; b) Rainfall trends considering monthly, seasonal and annual scale data series over the periods 1981–2015 in Kaligandaki basin. No of stations (out of 21) in MK test find significant positive-negative trends in 95% confidence levels.

only a few stations showed significant changes during different months except in the month of March where none of the stations showed significant changes. Maximum stations showed significant decreasing trend in the month of December (5 out of 22) with slope magnitude ranges between −0.8 mm/year and 0.0 mm/year whereas significant increasing trend in the month of August (2 out of 22) with slope magnitude ranges between 0.3 mm/year and 5.3 mm/year (Fig. S3). Similarly, in the case of Kaligandaki basin, a number of stations

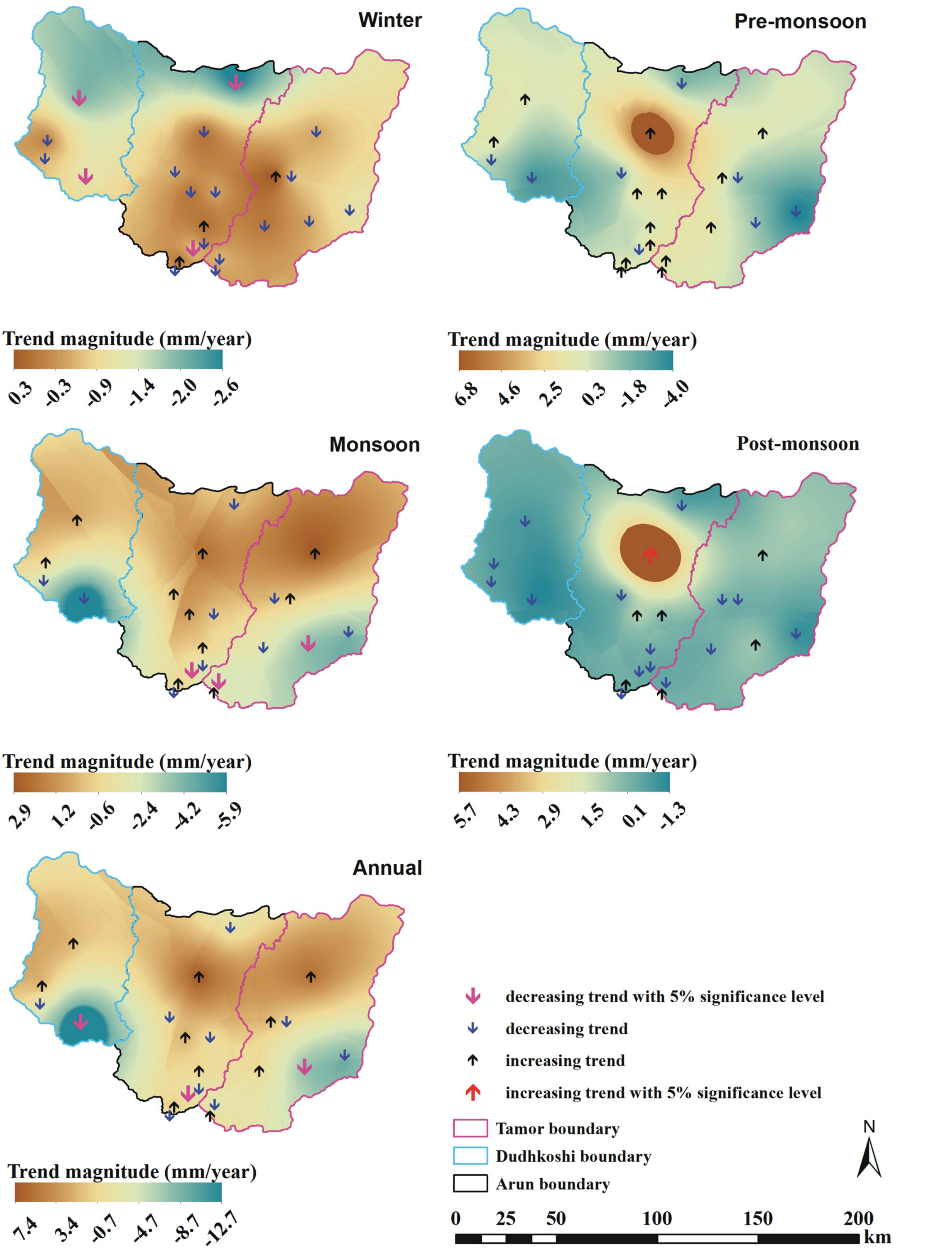


Fig. 6. Spatial distribution of stations with significant trends by Mann-Kendall analysis and interpolated trend magnitude (mm/year) resulted from Sen's analysis in seasonal and annual time series data over the period 1981–2015 for Koshi basin.

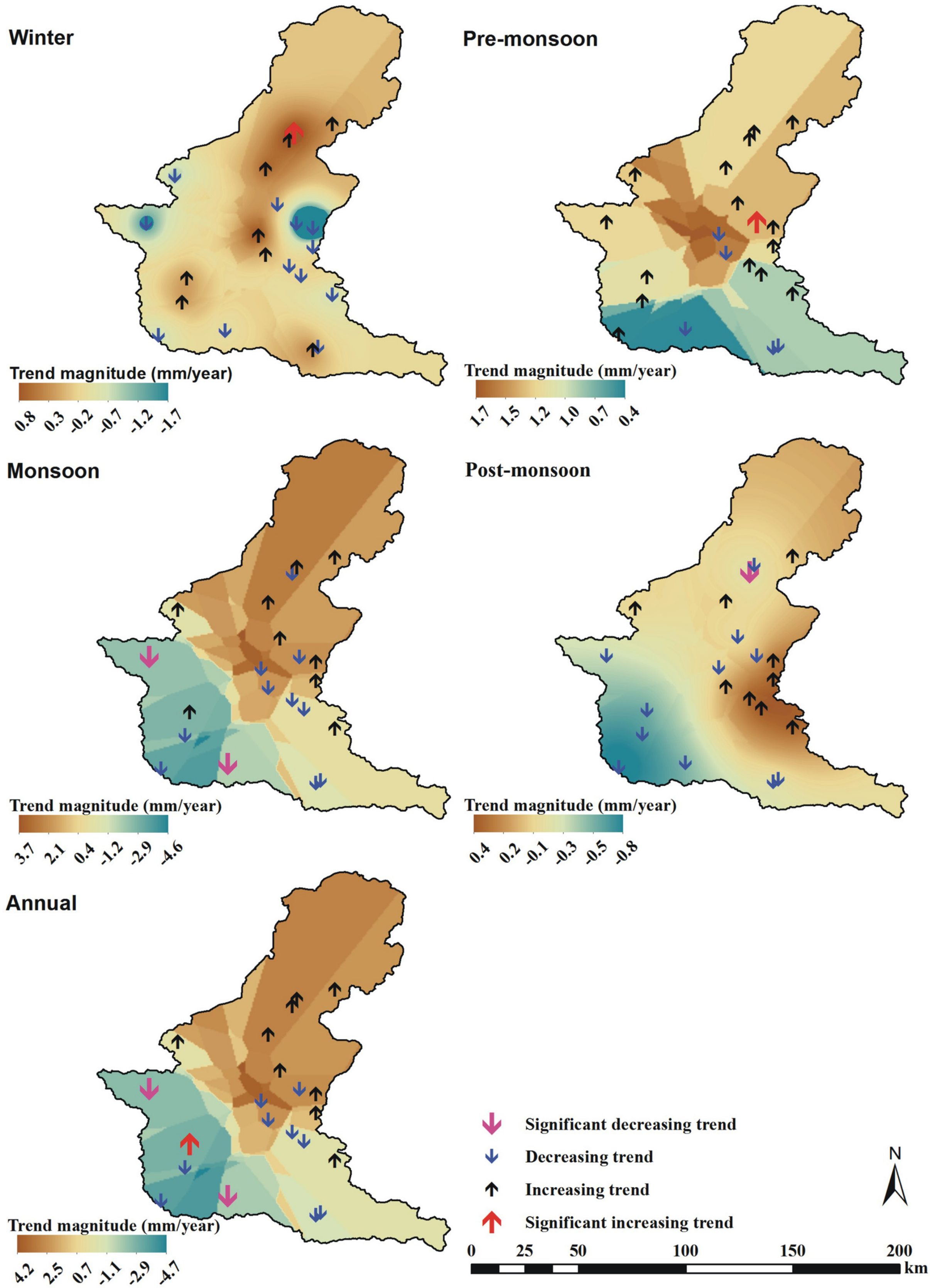


Fig. 7. Spatial distribution of stations with significant trends by Mann-Kendall analysis and interpolated trend magnitude (mm/year) resulted from Sen's analysis in seasonal and annual time series data over the period 1981–2015 for Kaligandaki basin.

Table 3
Results of Mann Kendall test statistic (Z) for monthly rainfall during 1981–2015. * and ** bold values show statistical significant increase and decrease at 1% and 5% confidence level. Negative and positive values indicate the decreasing and increasing trends.

Basin	Station Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Kaligandaki	Ridi bazar	−1.13	1.10	0.01	0.78	−1.32	−1.56	−1.79	−0.48	−1.79	−0.52	−1.79	**−2.20***
	Chapkot	−0.84	1.41	−0.90	0.53	−0.51	−0.48	−1.79	0.43	**−2.02***	0.07	−1.80	**−2.28***
	Garakot	−0.49	**2.11***	0.06	−0.17	−0.77	−0.28	−1.18	1.42	−1.76	0.33	**−2.27***	**−2.27***
	Benibazar	0.49	1.26	0.11	0.23	0.43	1.51	−0.36	0.41	−1.14	0.23	−1.75	−1.93
	Syangja	−1.05	0.44	0.03	0.23	0.37	−0.43	0.51	0.17	0.34	1.08	−1.51	**−3.22****
	Kushma	−0.60	1.95	0.70	0.28	−0.36	−0.51	−0.23	−0.16	−1.33	0.64	−0.87	**−2.12***
	Baglung	−0.37	1.34	1.04	−0.01	−0.80	0.51	−0.23	0.94	−1.62	0.84	−1.01	−1.80
	Tatopani	0.04	1.59	−0.16	1.48	0.74	1.78	0.40	−0.60	0.43	0.00	−1.29	−1.82
	Musikot	0.61	1.13	−0.63	0.33	0.87	1.52	0.76	1.55	−0.57	−0.06	−2.77	**−2.17***
	Tamghas	−0.40	1.39	−0.47	0.28	1.05	−0.14	−0.26	0.37	−1.62	0.30	**−2.44***	**−2.38***
	Karki Neta	−0.61	1.35	1.19	0.78	1.02	0.62	0.20	0.72	−1.70	1.48	−1.11	**−2.21***
	Lumle	−1.17	1.05	−0.55	0.14	0.14	0.06	0.92	−0.11	−0.28	0.60	−1.71	**−2.35***
	Kahanchikot	−0.80	0.92	−0.14	1.19	−0.37	−0.09	−0.09	0.48	**−2.36***	−0.24	**−2.38***	**−2.43***
	Ghandruk	−1.21	−0.91	0.20	0.03	1.14	0.20	1.51	**1.99***	1.82	1.26	−0.63	**−2.47***
	Bobang	0.00	−1.19	−0.24	−0.38	−0.07	0.09	−0.62	−1.24	**−2.73****	−0.27	−1.26	**−2.30***
	Lete	0.28	1.86	0.65	1.25	1.39	**2.06***	0.23	0.28	−1.48	1.28	−0.60	−1.31
	Gurja Khani	−0.94	0.23	0.37	0.75	−0.17	1.14	0.57	1.73	−0.34	1.00	−0.98	**−2.19***
	Thakmarpha	1.36	**2.34***	−0.14	1.93	−1.25	0.51	0.99	−0.62	−1.89	−0.47	−1.79	**−2.24***
	Ghorepani	−1.40	−0.58	0.61	**2.71****	0.80	0.80	−1.19	−1.36	**−2.24***	−0.17	**−2.05***	**−2.71****
	Jomsom	1.15	**2.10***	−0.50	1.21	0.33	1.42	1.79	1.35	−1.51	0.53	−0.67	−1.50
	Ranipauwa	0.71	1.48	0.00	1.00	−0.31	0.27	−0.07	1.90	−1.65	1.85	−1.00	**−2.32***
Koshi	Dhankuta	−0.91	−0.66	−0.10	0.48	0.82	−0.57	−1.36	0.03	**−2.76****	0.16	−1.59	**−2.04***
	Mulghat	−0.22	−0.47	1.14	0.80	−0.11	0.37	−0.54	0.85	−1.39	0.48	**−1.98***	−1.90
	Terhathum	−0.15	0.24	−0.21	0.28	0.94	−0.43	−0.07	1.22	−0.85	0.27	−0.81	−1.04
	Lungthung	−0.44	0.43	0.91	−0.81	**2.02***	0.68	−0.45	**2.58****	−0.17	0.71	−0.01	−1.32
	Taplejung	−0.97	0.16	−0.14	0.00	−1.02	0.82	**−2.19***	**2.02***	−0.74	0.45	−0.77	**−2.22***
	Memeng Jagat	−0.64	−1.36	−1.55	−1.70	−0.51	−1.28	**−2.24***	1.45	−1.53	−0.55	−1.69	−1.88
	Phidim	−0.59	−0.30	−0.41	−0.71	−0.57	−0.23	**−3.12****	0.62	−1.85	1.63	−1.22	−1.12
	Dovan	−0.75	1.06	0.71	0.00	0.23	0.14	−0.88	0.40	0.37	0.06	−0.06	−0.31
	Num	−0.36	0.60	0.70	1.36	0.65	−0.34	−1.25	1.65	1.36	**2.29***	1.95	0.69
	Chainpur	−1.04	0.04	0.10	**2.24***	−0.51	1.52	−1.73	1.08	−0.88	0.60	−1.07	−1.84
	Pakhribas	−0.79	−0.41	0.67	1.60	0.31	0.26	−1.33	−0.17	−0.34	0.48	−1.32	**−1.98***
	Leguwaghat	−0.04	0.57	−0.33	0.11	−0.20	1.48	−0.06	1.36	0.11	0.30	−1.73	−1.43
	Munga	−0.73	−0.75	−0.27	0.72	−0.06	**−2.05***	−1.68	−0.48	−0.34	0.00	−0.23	−1.69
	Tribeni	−0.51	−0.58	−0.21	0.88	0.30	1.14	−1.31	1.19	−1.09	0.00	−1.62	−1.41
	Chepuwa	−1.05	−0.97	−0.09	−1.11	0.65	−0.91	−0.89	0.09	−0.74	−0.24	0.09	**−2.55***
	Tumlingtar	−1.84	0.30	−0.17	1.25	0.00	1.45	0.31	1.59	−0.43	1.12	−1.17	−1.36
	Machuwaghat	−0.07	−0.34	0.23	0.20	−0.09	1.33	0.17	1.45	0.14	0.41	−1.12	−1.01
	Dingla	−0.96	−0.33	−0.51	0.43	−1.02	1.96	−1.28	1.19	−0.60	−0.26	−1.06	−1.16
	Chaurikhark	−1.38	**−3.01****	0.00	0.00	0.21	0.65	0.94	0.85	−1.08	−0.95	−0.34	**−2.03***
	Pakarnas	−1.47	0.03	−1.02	0.13	−0.68	−0.88	−1.73	0.77	−1.15	0.07	**−2.74****	−1.93
	Aisealukhark	**−2.05***	0.50	−0.70	−0.55	−1.58	−1.29	−1.29	0.44	−1.18	−0.77	**−2.13***	−1.47
	Salleri	−1.31	0.60	−0.10	−0.67	0.68	−0.23	−0.34	1.59	−0.23	−0.20	−0.24	−0.83

showing increasing trend has more months than decreasing trend with some exception of no trend (Table 3 and Fig. 5). The months of January, March, May, July and October showed no any significant trend. December month showed maximum significant decreasing trend with 16 out of 21 stations with slope magnitude ranges between −0.0 mm/year and −0.5 mm/year whereas February showed maximum significant increasing trend with 3 out of 21 stations with slope magnitude ranges between −0.3 mm/year and 0.8 mm/year (Fig. S4). The monthly spatial pattern of trend magnitude supports to their respective seasonal pattern except during transition month (Figs. 6, 7 and Figs. S3 and S4). For instance, the spatial variation of trend magnitude during May and June (transition period between pre-monsoon and monsoon season) showed a different pattern than other their respective months. Similarly, other transitions months i.e., September–October, November–December and February–March also support above statement between the post-monsoon, winter and pre-monsoon respectively.

4.2.2. Annual rainfall trend

For more information regarding long-term rainfall variation, MK trend test was furthermore carried out for annual rainfall. From the statistical test for Koshi basin, the annual trends were identified for rainfall data where more than half (12 out of 22) of the stations showed decreasing trend while the rest of the stations showed an increasing trend (Table 2 and Fig. 4). However, only three stations (Phidim, Munga and Aisealukhark of Tamor, Arun and Dudhkoshi sub-basins respectively) showed the significant decreasing trend and lies on the southern part of the basin (Figs. 4 and 6). The decrease in rainfall is due to the topography as this southern region lies at drier zone created between southern frontal and northern elevated mountains (Bohner, 2006). On the contrary, Sharma et al. (2000) studied rainfall data between 1947 and1993 and found an increasing trend in the Koshi basin of eastern Nepal. A similar result was observed in the investigation carried out by Nepal (2016) where they analyzed rainfall data in the Koshi basin and found an increasing trend in annual rainfall among 22 stations out of 36 stations while 14 stations have decreasing trend. Only two stations showed an increasing trend while the remaining one show decreasing trend. The reason behind such difference in the results is due to the different time period, changes in climate stations and different methodical approaches. The trend magnitude of annual rainfall (mm/year) is identified as regional wide mild positive and negative slopes (Fig. 6). Mainly, lower southern part of all sub-basins shows negative slope while the upper central part of Arun and Tamor sub-basins show the positive slope. The magnitude of the trend varied between −12.7 mm/year and 7.4 mm/year. Due to orographic lifting mainly on the southern slopes of Himalayan foothills where moist air flow collides causes heavy rainfall. These mountains act as a barrier which results in rain shadow effect and also causing a decrease in rainfall from east to west along the Himalayas and from south to north within them. Overall,

Table 4
Starting and abrupt change time determined by Sequential Mann-Kendall test (SQMT). Up and down arrows indicate the increasing and decreasing trends.

Sub-basins	Stations		Trend	Start of trend	Abrupt change	Significant trend
Tamor	Dhankuta	Monsoon	↓	1989	1990	2013
	Memeng Jagat	Annual	↓	1990	1992	No
	Phidim	Monsoon	↓	1991	1992	2015
Arun	Num	Post-monsoon	↑	1983	1984	1989
	Munga	Annual	↓	1990	1990	2011
		Winter	↓	1991	1998	2011
		Monsoon	↓	1995	1995	2010
	Chepuwa	Winter	↓	1997	1999	2008
Dudhkoshi	Chaurikhark	Winter	↓	1990	1990	1997
	Aisealukhark	Annual	↓	1985	1990	2011
		Winter	↓	1997	1997	2010
Kaligandaki	Ridibazar	Monsoon	↓	2000	No	No
		Annual	↓	1984	1984	2005
	Bobang	Monsoon	↓	1989	1992	2009
		Annual	↓	1989	1990	2013
	Jomsom	Winter	↑	1985	1985	2015
	Ghorepani	Pre-Monsoon	↑	1986	1996	2002
	Thakmarpha	Post-monsoon	↓	1987	1987	2014
	Musikot	Annual	↑	1992	1998	2000

aforementioned results coincide with some previous studies which were concluded with rainfall decreasing trend at the southern part of Mount Everest (Salerno et al., 2015; Xu et al., 2008; Yang et al., 2006).

In the case of Kaligandaki basin, MK test result of annual rainfall identified about half (10 out of 21) of the stations with decreasing trend and other 10 stations with increasing trend while 1 station didn't show any trend (Table 2 and Fig. 5). Among these trend, 2 (Ridibazar and Bobang) stations showed significant decreasing trend while only 1 (Musikot) station showed a significant increasing trend (Fig. 5). Even though these three stations lie on the south-west part of the basin (Fig. 7), stations with significant decreasing trend lie in valley whereas later one lies at windward side indicating the effect of topography (Bohner, 2006; Houze, 2012; Romatschke and Houze Jr, 2011). These aforementioned results are in agreement with the results of Panthi et al. (2015) with some exceptions, where they showed increasing annual rainfall trend. The exceptions are due to some difference in study area along with climate stations and time period. The trend magnitude varied between −4.7 mm/year and 4.2 mm/year (Fig. 7). Mainly, lower southern part of basin shows negative slope while the upper part shows the positive slope.

4.3. Rainfall shift analysis

The above tests provide information about rainfall conditions and their long-term changes. But they lack to exhibit certain changes during the analysis period. To overcome such problem from knowing the shift in rainfall, Sequential Mann-Kendall (SQMK) test was used. The analysis was carried out for the time series with the significant trend at the 95% level of significance. The analysis was conducted only for those time series with significant trend at 95% confidence level resulted in above analysis. The different stations have different shift change points for different time series as per the intersection between the curves of forward and backward series. The breakpoints calculated by SQMK test are shown in Table 4 and Figs. S5–S8. Generally, from 1989 to 2015, rainfall trend was found declining in the Tamor sub-basin as mentioned earlier section (Fig. S5). This significant declination in rainfall at different stations (Dhankuta, Phidim and Memeng Jagat) was started as early as 1989 but drastically accelerated during early 1990s. These accelerated trend became significant only in recent years, while in the case of Memeng Jagat station, it did not showed a significant trend after it exceeds the abrupt change point (Fig. S5a). Similarly, three stations of Arun sub-basin showed a significant trend, among which Num (post-monsoon) station showed increasing trend while, Munga (annual, winter and monsoon) and Chepuwa (winter) stations showed a significant decreasing trend (as showed in earlier section) (Fig. S6). Except Num station, the change point was found during 1990s and became significant during late or early 2010s. At Num station, the change point was found in 1984 and became significant after 1989. Furthermore, in the case of Dudhkoshi sub-basin, Chaurikhark and Aisealukhark stations showed abrupt declining in rainfall since 1985 (Fig. S7). At Chaurikhark station, winter rainfall trend decline and accelerated since 1990 and became significant after 1997. However, in Aisealukhark station, the curves cross each other in 1990s and became significant after 2010s. These results are somehow in agreement with previous studies which concluded that the southern part of Mount Everest showed an abrupt decrease of rainfall occurred in early 1990s (Salerno et al., 2015; Xu et al., 2008; Yang et al., 2006).

In case of Kaligandaki basin, most of the significant trends is declining since 1980s or early 1990s with some exceptions (Table 4 and Fig. S8). Even though Ridibazar station showed a decline in monsoonal rainfall, no any shift changes were found. Annual rainfall trend in Ridibazar and Bobang stations showed declining trend with shift change in the year 1984 and 1990 and became significant after 2005 and 2013 respectively. While at Musikot station, annual rainfall trend inclines and accelerated since 1998 and became significant after 2000. During the winter season, only Jomsom station showed increasing trend started in the year 1985 and since then it accelerated and became significant in the year 2015. Similarly, during pre-monsoon season, only Ghorepani station showed increasing trend started around 1986 but rainfall shift change was found after a decade which became significant only after 2002. Meanwhile, monsoon rainfall at Bobang station exhibited declining trend since 1989 which changes abruptly after the year 1992 and became significant after 2009. Similarly, during post-monsoon season, only Thakmarpha station showed decreasing trend started and accelerated since 1987 and hence became significant recently. Generally, the number of change points along with its associated year of change for a given sub-basin was almost similar to its respective neighbouring sub-basin. This result showed that the change points corresponded with a number of reported El Nino events showed by several different studies (Cai et al., 2014; Kumar et al., 2006; Pascolini-Campbell et al., 2015). For instance, the stronger El Nino events during 1982/83, 1997/98 showed common change points which were detected mostly throughout the study area, indicating the influence of large-scale oscillation in rainfall variation.

4.4. Periodicities of annual and monsoonal rainfall

As mentioned above, there are certain shift changes found in rainfall analysis during the study period. Other than local topography, it presumably related to the large-scale circulation like ENSO, QBO. Hence, multitaper method is used to elaborate the relationship between rainfall and large-scale circulation indices. As the data time series is short of about 35 years, the method used the time-bandwidth parameter $p = 2$ and the number of tapers $K = 3$ which is considered as best in a contest of climate studies (Mann and Park, 1996) and the results are shown in Fig. 8. Significant spectral peaks occurred during annual rainfall at 0.43 cycles/year ($p > 90\%$) at Kaligandaki basin while at Koshi basin, it occurred at 0.30 and 0.46 cycles/year ($p > 90\%$) (Fig. 8a and b). Similarly, during monsoon, the spectral peaks occurred at 0.42 cycles/year ($p > 90\%$) for Kaligandaki basin while, for Koshi basin, it occurred at 0.26 and 0.30 cycles/year ($p > 90\%$) (Fig. 8c and d). However, no any significant spectral peaks are found during winter rainfall of both the basins (Fig. 8e and f). The significant spectral peaks were identified at 2–5 years which were found to be consistent with the quasi-biennial oscillations (QBO) (2–3 year cycle) and ENSO

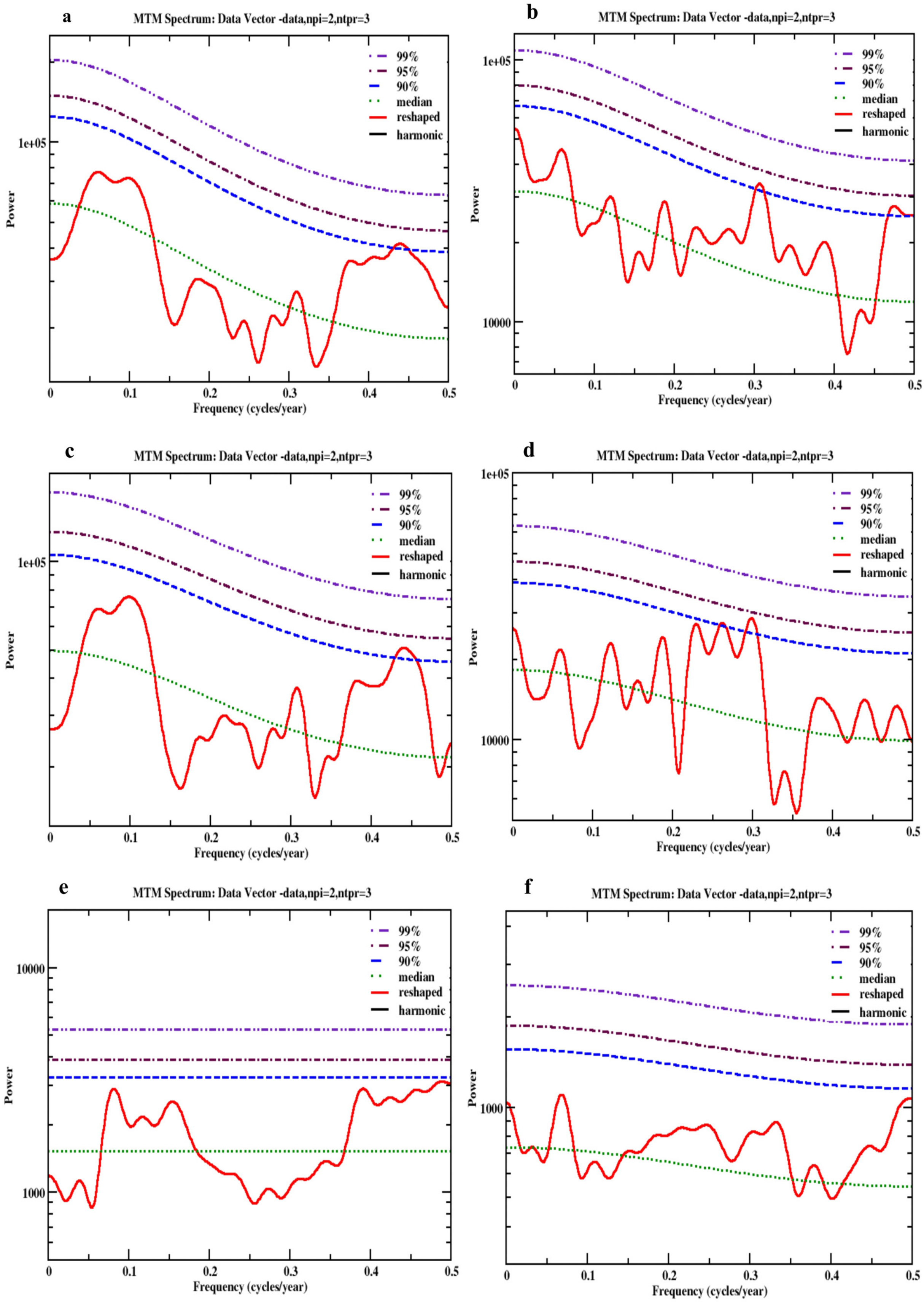


Fig. 8. Power spectrum (red line) by MTM of annual rainfall (a and b); monsoon rainfall (c and d) and winter rainfall (e and f) for Kaligandaki basin (Left) and Koshi basin (Right) with the bandwidth parameter $p = 2$ and tapers $K = 3$. The estimated noise background and associated 90, 95 and 99% significance levels are shown by four smooth curves, from the lowest to the highest. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(3–7 year cycle) related meteorological phenomenon (Allan et al., 1996; Allan, 2000; Bridgman and Oliver, 2006). So, those above results indicate that the QBO and ENSO have an effect on the inter-annual and seasonal variations in rainfall which further supports the arguments. In general, the above findings indicate some connection of rainfall with large-scale circulation indices on both the basins. This is in good agreement with previous studies which showed some influence about El Niño Southern Oscillations (ENSO) on rainfall in Nepal and its different parts of the country (Gaire et al., 2017; Madan and Ikeda, 2009; Shrestha et al., 2000).

5. Conclusions

In the sub-basins of Koshi basin, a similar pattern of increase in rainfall from south to north was found throughout all seasons indicating low rainfall in the southern region. While, in case of Kaligandaki basin, only pre-monsoon and monsoon seasons showed a similar pattern of rainfall, which is totally different from Koshi basin. That is, relatively low rainfall occurs in the northern region than that of southern region. Both the basins showed the exception of high rainfall pocket zone, which lies in the northern region of Arun sub-basin and south-east region of Kaligandaki basin. The period of transition months between seasons showed an almost similar pattern but different from other months of respective seasons. Similarly, the spatial variation of annual rainfall was also found a similar pattern to the monsoon for both the basins as these basins are dominated by monsoon season.

The results of seasonal trend tests showed decreasing trend in most of the stations except pre-monsoon. Only 4 (3) stations during winter (monsoon) season showed a significant decreasing trend in Koshi basin while one station showed significant increasing trend during post-monsoon season. However, in Kaligandaki basin, 2 (1) stations showed significant decreasing trend during monsoon (post-monsoon) season whereas only one station each showed significant increasing trend during winter and pre-monsoon season. Similarly, during annual rainfall trend analysis, 3 (2) stations showed significant decreasing trend in Koshi (Kaligandaki) basin while only one station of Kaligandaki basin showed a significant increasing trend. These noticeable significant decreases were mainly observed in the lower southern and some central parts of the study area.

Although the trend shifts analysis for Koshi basin was identified change point during 1990s, significant shifts were observed only after 2010s. However, for Kaligandaki basin, most of the change points are found during 1980s or early 1990s, but most significant shifts were observed in recent years. Even though, Memeng Jagat (Koshi) station and Ridibazar station (Kaligandaki) being the exception, former showed shift change without significant while latter one didn't show either of it. Finally, periodicity analysis for both basins showed the connection of rainfall with large-scale circulation indices since rainfall fluctuates on cycles that are predominantly 2–5 years long which were found to be consistent with the quasi-biennial oscillations (QBO) (2–3 year cycle) and ENSO (3–7 year cycle) -related meteorological phenomenon.

The results of this study benefit future studies on climate change and water resource planning. However, some more investigations and comprehensive analysis of the rainfall are needed to seek the causes and factors affecting these trends and relationship with climate change. Additionally, wider ranges of temporal and spatial climatic data are strongly recommended for further future study along with an additional trend analysis method to verify this concluded result.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosres.2018.08.027.

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